Dwarf Galaxies with Gentle Star Formation and the Counts of Galaxies from the Hubble Deep Field

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ABSTRACT

In this paper the counts and colors of the faint galaxies observed in the Hubble Deep Field are fitted by means of simple luminosity evolution models which incorporate a numerous population of *fading* dwarfs. The observed color distribution of the very faint galaxies allows now to put constrains on the star formation history in dwarfs. It is shown that the star-forming activity in these small systems has to proceed in a *gentle* way, i.e. through episodes each one lasting much longer than a simple instantaneous burst of star formation. By allowing dwarfs to form stars in this *gentle* way the number of predicted red remnants is severely reduced, in good agreement with the observations. Then, if the faint counts are to be fitted by means of dwarfs, the simple model for dwarfs forming stars in single, very short episodes is challenged, and a more complex star formation history has to be invoked. Recent observational evidence supporting this new dwarf models are also discussed.

Subject headings: cosmology:observations - galaxies:evolution - galaxies:photometry

To appear in *The Astrophysical Journal*, May 1997

1. Introduction

The Hubble Deep Field (HDF; Williams et al. 1996) has provided the deepest view so far achieved from the Universe. Metcalfe et al. (1996) have computed galaxy counts to the faintest limits (U=26, B=29, R=28 I=28), shown to be in good agreement with ground-based data at brighter levels (B=28.2). The information on galaxy formation and evolution that can be obtained from the HDF is striking, as it has been shown during the past months.

The HDF has a very small field of view (5.3 arcmin^2), and so the dominant population of galaxies is built up by very faint objects. In fact, the number of galaxies with apparent magnitude I$\sim$ 28 exceeds that of galaxies with I$\sim$ 23 by almost a factor of 20. Which kind of galaxies constitutes the bulk of objects in the HDF?

The first result that comes out after a first look to the HDF counts is that, even if there is some flattening in the deepest magnitude bins, down to the faintest limits the counts continue to increase with a quite steep slope. This is a difficult result to interpret in *any cosmological setting,* not just because of the cosmological turn-down effect of the volume (especially if $q_0 = 0.5$) but also because of the Lyman break being red-shifted into the different photometric bands (approx z=3, 4, 5 and 6 for U, B, R and I respectively), hiding any galaxy beyond those limits. An observational confirmation of the presence of the Lyman break is found in the Keck-spectra of galaxies at $z \sim 3$ (Steidel, Pettini & Hamilton 1996). In fact, as I will show in the next sections, the level of counts is not easy to predict with *pure* luminosity evolution models, no matter the value of q_0 used.

The level of counts at the faint limits can be increased by including merging in the models, as was first suggested by Guiderdoni and Rocca-Volmerange (1991) and by Broadhurst, Ellis & Glazebrook (1992) for an spatially-flat cosmology. The number-density of galaxies could increase as we look back toward higher redshifts, galaxies being splitted up into the fragments that eventually will merge to build up the present-day population of galaxies.

However, the rate of merging has recently been claimed to be *moderate,* (eg. Barger et al. 1996; Dickinson 1996; Griffiths et al. 1996). Ellis et al. (1996) argue that the very little scatter in the U-V color of ellipticals in clusters at $z \sim 0.5$ is consistent with the previous suggestion by Bower, Lucey & Ellis (1992; from their study of galaxies in the Coma cluster) that ellipticals formed at high redshift and since then have *passively* evolved. Then, if ellipticals were assembled by merging of smaller fragments this had to occur at very early times (Kauffmann 1996).

Some authors (eg. Koo & Kron 1992) have suggested that the bulk of faint blue galaxies in the deep counts could be intrinsically faint galaxies (dwarfs) located at low redshift. Even in an Einstein-de Sitter (EdS) model, the contribution of a (numerous) population of dwarfs to the counts will continue to increase with an Euclidean slope becoming the dominant population at the faint levels, as first noticed by Driver et al. (1994). Babul & Ferguson (1996) show that by including a population of "fading" dwarfs the level of counts can be easily increased to the observed levels without the recourse to number-density evolution (which, in any case, might exist).

In this paper I try to get new insight into the role of dwarfs to interpret the counts of faint galaxies, in an attempt to constrain the star formation process in these low mass systems by means of the galaxy colors in the HDF. Whereas Babul & Ferguson assume that the star formation in dwarfs takes place in single, very short ($\sim 10^7$ years) episodes, I will argue that in order to fit the counts to the faintest levels by means of dwarfs *without over-predicting* the number of red, faint remnants, the star formation should take place in a more *gentle* way. In fact, as discussed below, analysis of the photometry of individual stars in nearby dwarfs (Smecker-Hane et al. 1996) show that dwarfs go through episodic bursts each one lasting $\sim$ 1 Gyr.

The modeling of bright and dwarf galaxies to fit the counts is presented in §2. §3 is devoted to the comparison of the model predictions and the counts, colors and angular sizes of galaxies in the HDF. A brief discussion of the results can be found in §4, and the summary and conclusions in §5.

2. Modeling galaxy evolution to fit the deep counts

In order to get information on galaxy evolution from the deep counts of galaxies two different approaches have been followed up to now. The *classical* one, pioneered by Tinsley (1972; although she was trying to understand the Hubble diagram rather than the counts), Kron (1978), Koo & Kron (1980) and Shanks (1980), takes as the starting point the popu-

lation of galaxies at present (namely, the z=0 Luminosity Function - LF) tracing back the evolution of the luminosity by assuming a redshift of formation (z_{for}) and a Star Formation Rate (SFR). A more sophisticated approach is the one followed by eg. White & Frenk (1991), Kauffman, Guiderdoni & White (1993), Cole et al. (1994) and Baugh, Frenk & Cole (1996), in which the starting point is the power spectrum of primordial density fluctuations predicted by the assumed theory for structure formation, followed by a *recipe* for the formation of the *visible* galaxies in which the dynamics of the gas, cooling and feedback processes are included.

In this paper I will follow the traditional approach of tracing back the evolution of the population of galaxies. Even if the semi-analytical models are undoubtedly proving to give interesting insight on the problem of galaxy formation and evolution, still the *flexibility* of the simpler approach and the fact that it does not rely on any specific theory for structure formation can give useful learning in our interpretation of the deep counts of galaxies.

2.1. Bright Galaxies

The population of "bright" galaxies has been splitted up into 3 main types: Ellipticals (E), Spirals (S) and Irregulars (Irr). The z=0 LF (LF0) has been taken from Efstathiou et al. (1988) with the morphological mix by Ellis (1983). To compute the evolution of the galaxy luminosities I used the spectrophotometric models for stellar population synthesis by Bruzual & Charlot (1993; new version of 1995). For each type of galaxy there are 3 parameters that we can adjust, with the constraint that the z=0 model-spectrum has to resemble the observed spectra of nearby galaxies of the type being modeled. These parameters are: the redshift of galaxy formation (z_{for}), the Star Formation Rate (SFR) and the Initial Mass Function (IMF). In this work I follow the suggestions given by Pozzetti, Bruzual & Zamorani (1996) of using a Scalo IMF for E and S, because it provides of a "milder" luminosity evolution and so the amount of high-redshift galaxies, observed to be very small in redshift surveys, is reduced. Similar results can be achieved with the Salpeter IMF, provided that extinction by dust is also included in the models (eg. Wang 1991; Franchescini et al. 1994; Koo & Kron 1995; Campos & Shanks 1996). As shown in Table 1, the SFR for E and S is taken to decay exponentially with time, whereas for Irr I consider a Salpeter IMF with a constant SFR. For the open models ($q_0 = 0.05$) the redshift of formation was taken to be $z_{for} = 4$ (Age = 15 Gyr; throughout this work: $H_0 = 50$ km s^{-1} Mpc^{-1}), whereas for the EdS model $z_{for} = 7$ (Age=12.7 Gyr). The dimming of the luminosity by the Lyman alpha forest (Madau 1995) and Lyman break is considered in the modeling of the counts and redshifts. Number density evolution is not included, even if it might exist at "moderate" rates, as already mentioned in the introduction.

2.2. A phenomenological model for dwarfs

Dwarf (intrinsically faint) galaxies do exist. We see them everywhere in large numbers. In fact, it has been shown that they may constitute up to 50% of the whole population in nearby clusters (Binggeli, Sandage & Tamman 1985; Ferguson & Sandage 1991. See also Trentham 1996). Dwarfs display a whole variety of properties in terms of shapes, colors and spectral features, while sharing in common the small sizes and low metal contents. This last property strongly suggests that the star formation history in these small systems may have followed a different evolutionary path than in normal galaxies. On this respect an explanation was first proposed by Dekel & Silk (1986), who showed that the shallow potential well in these low-mass galaxies may not be able to retain the gas after the subsequent galactic wind following an episode of star formation. Being stripped off the gas, the galaxies cannot form stars any longer, and so their luminosities, as the massive stars evolve, fade away. Following this line of arguments, Babul & Rees (1992) suggested that the gas may not be entirely lost, but trapped in the outer parts of the dark halo from where could re-collapse, given vise to new episodes of star formation. Whether the gas is completely lost will depend on the mass of the galaxy but also on the pressure of the environment, that could confine it. This scenario is in all similar to that first proposed by Davies & Phillips (1988), who suggested that the star formation in dwarfs may proceed in the form of intermittent bursts followed by long quiescent periods.

The importance of accounting properly for the presence of dwarfs in the modeling of the deep counts was already shown by Driver et al. (1994). A much more elaborated model was recently worked out by Babul & Ferguson (1996), who very appropriately "baptized" the dwarfs as "boojums == blue objects observed just undergoing moderate starburst". In

this work it is claimed that dwarfs may arise in large numbers in hierarchical models for structure formation at high redshifts, while the star formation is delayed until $z \sim 1$ due to the photoionization of the interstellar matter by the UV background ionization (Babul & Rees 1992).

Dwarfs are assumed to form continuously since z=1 up to now (see also Babul & Ferguson 1996). Because of the "classical" approach chosen to model the deep counts, this continuous formation of dwarfs is simulated by allowing them to form in contiguous generations each one following the previous one by 0.5 Gyrs. The LF for dwarfs is assumed to have a Schechter-like form, with a slope $\alpha = -2$. The reason for this very steep slope is based on the fact that in hierarchical clustering the distribution of small halos is a steep function of the mass. However, as discussed later, the choice of α won't alter any of the basic conclusions of this work.

Two different types of dwarfs are tested (called B=0.05 and B=0.5). In both of them the star formation is assumed to proceed in the form of a single burst (i.e. constant star formation) lasting 5×10^7 and 5×10^8 years for models B=0.05 and B=0.5 respectively. The masses of dwarfs are the same in both models: $4.7 \times 10^{10} M_\odot$ for an L_* dwarf (total mass; I assume that the baryonic matter is $\sim 1\%$ of the total mass). The mass of the smallest dwarfs is 4.7×10^8, or five magnitudes fainter than M_*. In the *peak* of star formation this corresponds to a magnitude in B (assuming a Salpeter IMF) of -18.5 and -20 for B=0.5 and B=0.05 respectively.

The number density of dwarfs is a free parameter chosen to fit the B-band counts to the faintest limits. For each generation $\Phi^*(g(z)) = \Phi^*(g(z=0)) \times (1+z)^n$, where $g(z)$ refers to the generation formed at a redshift z. Two different cases are tested: $n = 0$ and $n = 3$. In the later, dwarfs are assumed to form more numerously as higher is the redshift of formation.

3. Dwarfs with gentle star formation and the deep counts

3.1. HST counts as a function of morphology

The unprecedented high-resolution imaging capability of the Hubble Space Telescope makes now possible to study the shape of very distant (faint) galaxies. Deep counts *as a function of morphological type* have recently been published (Driver et al. 1995; Glazebrook et al. 1995a; Abraham et al. 1996) down to I=25. It has been shown that the counts of E galaxies increase much more slowly than the counts of irregular/peculiar systems (also called "weirdos" galaxies; hereafter W). In fact, the counts of E show a small evidence for flattening at I$\sim$ 25. At I=18 E are more numerous than W by a factor of $\sim$ 3, while at I=25 W become more numerous than E by almost a factor of 2, reaching a level of counts comparable to that of S. These results have led to questioning the extent to which the Hubble system provides an adequate description of the morphology of galaxies at high redshifts.

The I-band counts splitted into the 3 morphological types (E, S and W) are shown in Figure 1 together with the model predictions. As it can be seen in the Figure, the *pure luminosity evolution models* (PLE) provide reasonable predictions for the counts of E and S, while severely under-estimate the number of W unless a (numerous) population of dwarfs is included (see Table 2 for more details on the dwarf models shown).

3.2. B-I color distribution

The fact that PLE models may have problems to predict the level of counts at very faint magnitudes is further evidenced in Figure 2. In this Figure it is shown the distribution of B-I colors for the galaxies in the Hubble Deep Field (Metcalfe et al. 1996), for galaxies selected according to their magnitudes in the I-band (top panels) and in the B-band (bottom panels). To put the HDF counts into the standard Johnson system in order to compare the HDF results with ground-based data (as in Figures 6a-d, where deep counts from a variety of sources are shown), it is necessary to use certain color conversions. The galaxy counts shown here were worked out by Metcalfe et al. (1996; 1997) who used the synthetic color transforms of Holtzman et al. (1995) and the published values of the HDF zero-point conversion from STMAG to Vega system. The details of the procedure can be found in Metcalfe et al. (1997). As shown in Metcalfe et al. (1996), there is an excellent agreement between space and ground-based data down to the faintest limits (e.g. $B \sim 28.2$, the limiting magnitude of the "Herschel Deep Field").

Together with the data, they are plotted predictions from PLE models. It is important to notice that the models *are not normalized to the number of galaxies in the HDF for each magnitude bin*, but just correspond to the predicted number of galaxies to be

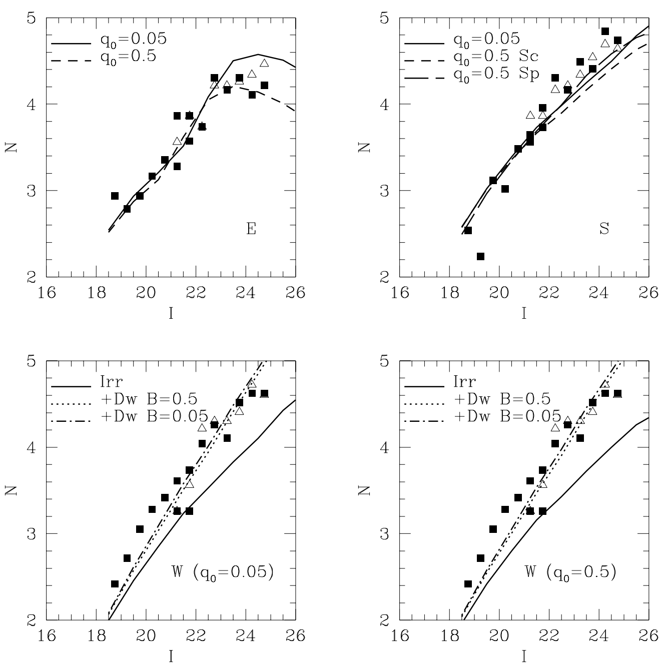

Fig. 1.— The counts of galaxies as a function of morphological type (data kindly provided by R. Abraham) in the I (Kron-Cousins) band. Together with the data there are shown pure luminosity evolution models with and without a population of dwarfs to fit the counts of “weirdos” (W) galaxies. In top panels there are shown counts of E and S galaxies. Solid and dashed lines are for $q_0 = 0.05$ and $q_0 = 0.5$ PLE model predictions respectively. For S both a Salpeter IMF (short dashed line) and a Scalo one (long dashed line) were considered. In bottom panels the counts of W are plotted, together with model predictions (q_0 = 0.05 - left panel and q_0 = 0.5 - right panel). Solid lines are the predictions when only a population of Irregulars is considered, whereas dashed lines are predictions from models including a population of dwarfs with a burst length of B=0.5 Gyr (dot lines) and B=0.05 Gyr (dot-dashed lines). For details on the modeling see Tables 1 and 2 and text.

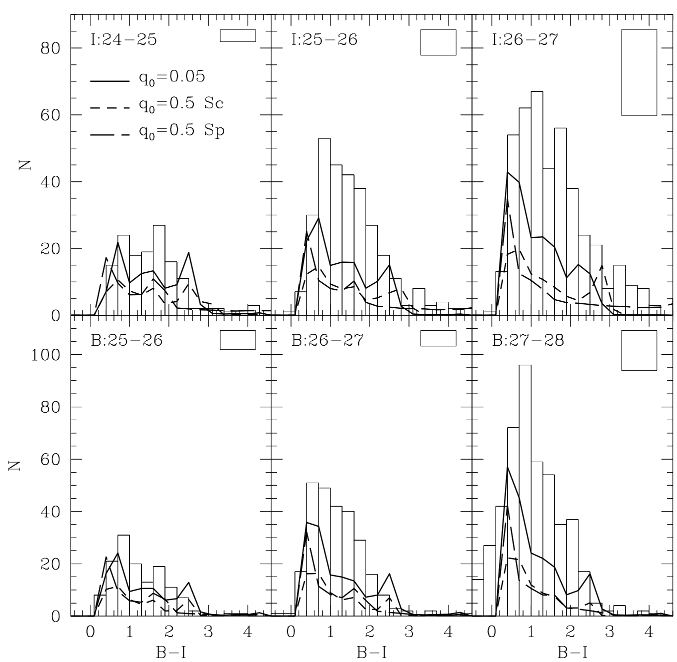

Fig. 2.— The B-I color distribution of faint galaxies in the HDF selected in the I-band (top panels) and B-band (Johnson; bottom panes) for different magnitude bins. The boxes in each panel corresponds to the incompleteness. Also there are shown predictions from pure luminosity evolution models. The models are not normalized to the number of galaxies in each magnitude bin but corresponds to the expected number of galaxies to be seen in the HDF field of view for each model.

seen in the HDF field of view. The normalization is fixed by the assumed values of Φ^* (see Table 1), which already corresponds to a *high* normalization, B$\sim$ 18. To the eye, the color distribution from PLE models seems to be a good match to the data if models had been normalized to the total number of galaxies in each magnitude bin. However if we did so, the deep counts would be over-predicted up to very faint levels. For example, in the $q_0 = 0.05$ model, data and predictions almost agree for $24 < I < 25$, but to fit the data for fainter bins with the same model we would have to multiply the normalization of the model by almost a factor of 3. Therefore the result which emerges is that, even if the predicted color distribution is similar to the observed one, a match to the data requires a normalization inconsistent with the counts. A remaining question is that of the very red high-z Lyman break galaxies. For the open model, because $z_{for} = 4$ there are no Lyman-break galaxies to be detected in the B-band (i.e. the break enters the B-band at $z \sim 4$, and so these galaxies would show up as very red in $B - I$ if they were located at $z > 4$). In the EdS models $z_{for} = 7$, and so the situation is different. However, because the volume element for $z > 4$ when $q_0 = 0.5$ is very small, the contribution of these galaxies is negligible.

As said before, none of the models is able to provide a reasonable fit when using the appropriate normalization. Interestingly, as we approach fainter limits, the models more severely under-predict the number of *red* faint galaxies (i.e. B-I$\sim 1-2$) observed.

The same plot is shown in Figures 3 and 4 (for $q_0 = 0.05$ and 0.5 respectively), although now the models include the dwarf population (n=0 case). As expected, the level of counts increases and the color distribution is much better reproduced. It becomes however clear that the star formation rate assumed for the dwarfs is a "key" issue to reproduce the data. The B=0.5 model giving a much better fit to the color distribution than the B=0.05 one.

As shown in Table 2, the number density of dwarfs in the B=0.05 model is larger than in the B=0.5 one for almost a factor of 2. The reason is found in the restriction imposed that the model has to be able to (approximately) reach the observed level of counts in the B-band. In the B=0.05 model, because the galaxies form the bulk of stars during a shorter period, fading away afterwards, the number of dwarfs required to fit the B-band counts is larger. This is simply due to the fact that the probability of observing a B=0.05

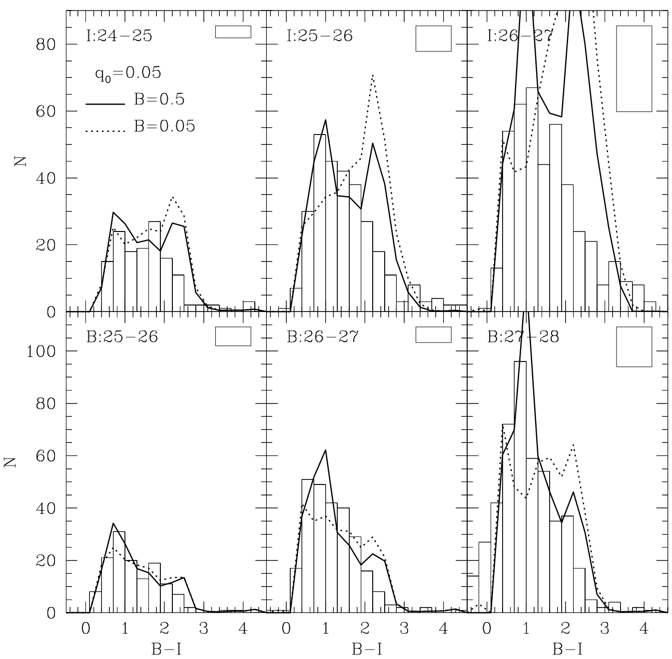

Fig. 3.— The same than Figure 3, but models now incorporate a population of dwarf galaxies with the star formation lasting 0.05 and 0.5 Gyr ($q_0 = 0.05$).

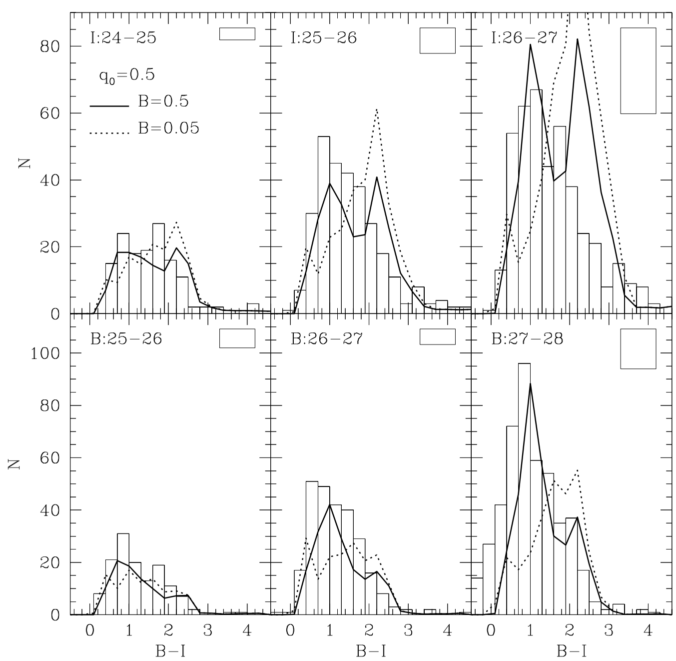

Fig. 4.— The same than Figure 3, but models now incorporate a population of dwarf galaxies with the star formation lasting 0.05 and 0.5 Gyr ($q_0 = 0.5$).

dwarf while exhibiting *blue* colors (i.e. in the "boojum" phase) is smaller than for a B=0.5 one. As a result, the B=0.05 model predicts a large population of red remnants which is not seen in the color distribution of the HDF galaxies. The disagreement is even worse if $q_0 = 0.5$.

The fit to the color distribution provided by the B=0.5 model is quite reasonable. It is only for the I=26-27 magnitude bin where model and data show disagreement, the model predicting a larger number of red (B-I$\sim 2-3$) galaxies than it is observed. However for this magnitude bin the incompleteness is large (see box in the Figures), and the galaxies without measured color (i.e. those detected in the I-band image but not in the B-band one) are expected to be red, i.e. too faint (B$\sim 29-30$?) to be detected.

It is interesting to notice that the shorter the star formation period in dwarfs (notice that Babul & Ferguson use $\sim 10^7$ yrs) the larger the number of (unobserved) remnants and vice-versa. Therefore if we want to fit the counts to the faintest levels by means of dwarfs, the star formation has to proceed in a more "gentle" way.

In order to test the effect of the rate at which dwarfs are being formed, I show in Figure 5 the same plot with predictions from B=0.5 models with two different rates of dwarf formation: n=0 (formation of dwarfs constant with time) and n=3 (formation of dwarfs decreases with time). The differences between the two are not as large as between the B=0.05 and B=0.5 models. Still it can be seen that in the n=3 case the number of red remnants in the I=26-27 bin is larger, as it is expected. Nevertheless the data does not allow a clear distinction between the two models.

3.3. Deep counts and redshift distributions

The deep counts in the K- (data taken from Djorgovski et al. 1995; Gardner et al. 1996a, 1996b; Soifer et al. 1994; McLeod et al. 1995; Glazebrook et al. 1995), I- (Metcalfe, Shanks & Fong 1995, Metcalfe et al. 1996a; Driver et al. 1994, 1995; Glazebrook et al. 1995; Smail et al. 1996; Lilly, Cowie & Gerdner 1991; Tyson 1988; Hall & Mackay 1984; Koo 1986), B- (Metcalfe et al. 1991, 1995, 1996a; Lilly et al. 1991; Tyson 1988; Couch & Newell 1984; Infante, Prittchet & Quintana 1986; Jones et al. 1991; Koo 1986; Kron 1987; Maddox et al. 1990) and U-band (Jones et al. 1991; Metcalfe et al. 1996; Guhathakurta, Tyson & Majeswki 1990; Koo 1986) are shown in Figure 6a-

d together with various model predictions for B=0.5 and 0.05 and $q_0 = 0.05$ and 0.5. (Because the counts are plotted in a logarithmic scale, they have been normalized by subtracting the corresponding "best" fit at brighter levels in order to expand the scale). It must be noticed here that the HST F300W filter is not very close to the standard U band, what complicate any comparison between HDF and ground-based data (see Metcalfe et al. 1997). Because the main source of data at the very faint limits is the HDF, the comparison between models and data in the U basspand must be taken with caution not only because of the uncertainties in the color conversion but because it can affect the number of Lyman dropouts as the F300W wavelength is shorter than the standard U-band one.

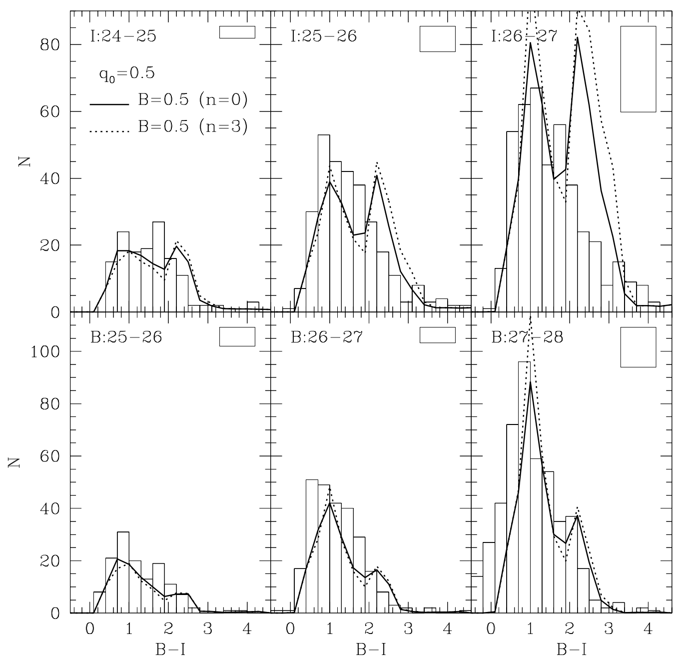

Fig. 5.— The same than Figure 3, but models now incorporate a population of dwarf galaxies with the star formation lasting 0.5 Gyr. The rate of dwarf formation with redshift is assumed to be $\Phi^*(g(z)) = \Phi^*(g(z=0)) \times (1+z)^n$. Here two models are tested: n=0 and n=3 ($q_0 = 0.5$).

In the K-band all 5 models give good predictions, although it would seem that the EdS case fits the data slightly better. In particular the shoulder (clear change of slope) seen at K$\sim$ 10 is very nicely reproduced. Notice that there is very little difference between the B=0.5 and B=0.05 models, the reason being that the contribution of the dwarfs to the K-band counts is only noticeable at very faint levels. In the other bands all 5 models are marginally consistent with the data, although the B=0.5 case give more consistent fits. For example, the B=0.05 $q_0 = 0.5$ model clearly over-predicts the I-band counts while under-predicting in the U-band. (Notice that the number of Lyman dropouts could be under-predicted because, as pointed out above, the F300W wavelength is shorter than the standard U-band one used in the models. This would affect the modeling in the sense of "over-predicting" the counts.) It should be noticed that the I-band counts are better fitted by EdS models than by open ones. Faintwards than $I \sim 26$ open models over-predict the counts, especially when B=0.05.

A further test to the models can be done by means of the redshift distribution of galaxies n(z) selected in different photometric bands. In fact the very early PLE models (eg. Metcalfe et al. 1991) that were successful in fitting the deep counts faced some problems with the absence of a *high redshift tail* in the observed n(z). These first discrepancies were solved by including further ingredients in the modeling, like the presence of dust (eg. Wang 1991; Franchescini et al. 1993; Gronwall & Koo 1995; Campos & Shanks 1996) or variations in the IMF (Pozzetti et al. 1996). Also the introduction of merging (Guiderdoni & Rocca-Volmerange 1991; Broadhurst et al. 1992) helped to

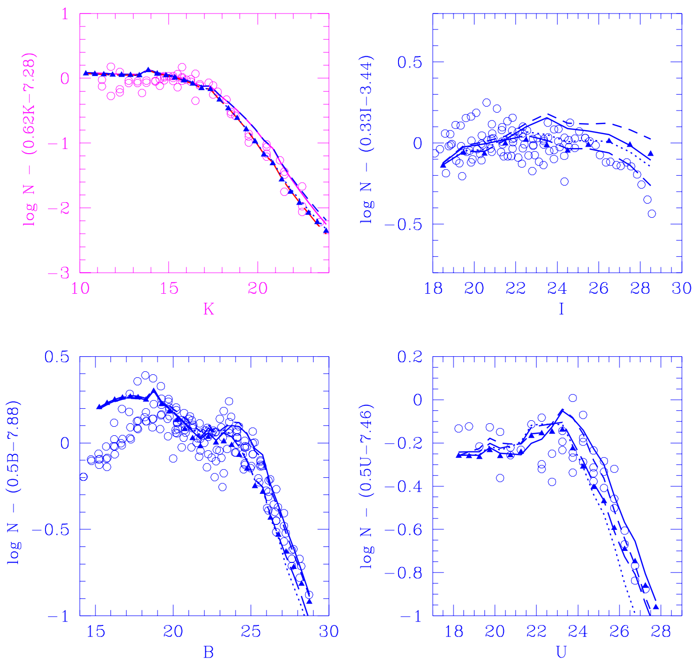

Fig. 6.— The deep counts of galaxies (per 0.5 mag per sq deg) in the K-, I-, B- and U-band (open circles; data taken from the literature. See text for references). Predictions from different luminosity evolution models with dwarfs are shown: triangles - ($q_0 = 0.5$ B=0.5 n=3); solid lines - ($q_0 = 0.05$ B=0.5 n=0); short dashed lines - ($q_0 = 0.05$ B=0.05 n=0); long dashed lines - ($q_0 = 0.5$ B=0.5 n=0); dot lines - ($q_0 = 0.5$ B=0.05 n=0).

solve the problem.

Here I'll use the sample of Colless et al. (1991; 1993) for galaxies with B:21-22.5, the recent survey by Cowie, Songalia & Hu (1996) for galaxies with B:22.5-24 and K:18-19, and the Canada-France Redshift Survey (CFRS; Crampton et al. 1995) for galaxies in the magnitude range I=17-22. The n(z) for the 4 samples are shown in Figure 7 together with model predictions. As can be seen, the n=0 models face some problems as slightly over-predict the number of low-z galaxies in Colless et al. (which is an almost "complete" sample). The number of very low-z galaxies is severely reduced when $n > 0$ (i.e. if the formation of dwarfs decreases with time). It is in any case interesting to point out that it is usually claimed (eg. Glazebrook et al. 1995b) that the un-identified galaxies in deep redshifts surveys are likely to be at high-z. The reason given being that the redshifts could not be measured because the main spectral features (like the frequently strong [OII]λ3727 emission line) are redshifted outside the optical spectral window. However it may happen that some "still-blue and luminous" dwarfs show a featureless spectrum, and so their redshifts are difficult to be measured. To illustrate this it is shown in Figure 8 the evolution with time of the [OII]λ3727 equivalent width and B-I color after a single burst of star formation. As soon as the massive stars evolve (which happens very fast) the equivalent width drops to zero, as there are no UV photons capable of ionizing the interstellar medium. While the colors remain blue for quite a longer period of time due to the bulk of intermediate mass stars still in the main sequence. Therefore, some of the un-identified objects might be dwarfs at low-z, still blue and luminous but in which the star formation just ceased.

In order to give the reader a better view on the behavior of the models, in Figure 9 they are plotted predictions for the redshift distribution of galaxies at fainter magnitude bins (i.e. $24 < B < 25$, $25 < B < 26$, $26 < B < 27$ and $27 < B < 28$). As expected for dwarf-rich models, at the very faint limits most galaxies are located at low redshifts (i.e. $z < 1$). There are however differences from model to model. For example, it can be seen that the B=0.05 models predict a higher percentage of galaxies at $z < 0.2$ than the B=0.5 ones, especially in the faintest bin. Also, the distribution is shifted toward higher redshifts when n=3 instead of n=0.

As a further test to the models, in Figure 10 it is plotted the z=0 LF used, together with the LF mea-

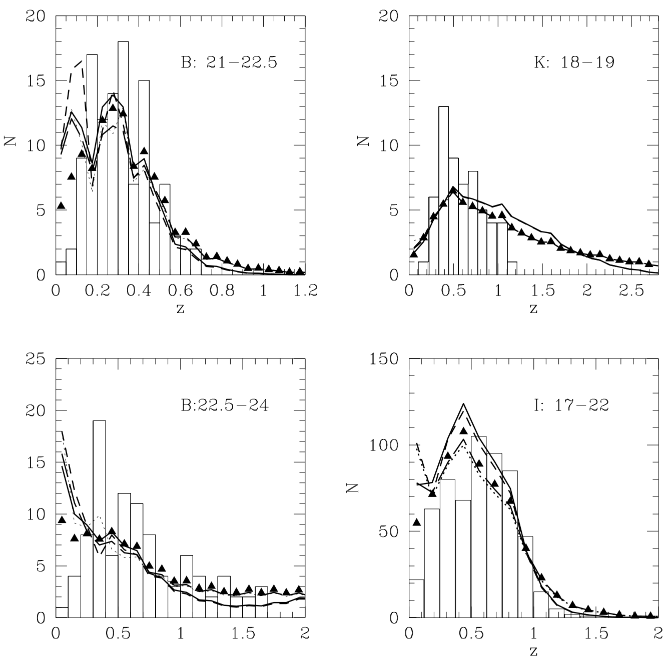

Fig. 7.— The n(z) redshift distribution of galaxies selected in different magnitude ranges (data taken from the literature. See text for references). The incompleteness rate (i.e. galaxies for which the redshift could not be measured) are: $\sim$ 12% for B:21-22.5, $\sim$ 15% for I:17-22 and $\sim$ 20% for K:18-19 and B:22.5-24. Lines are predictions from n=0 dwarf models as in Figure 6. Notice that B=0.5 models predicts less amount of very low-z dwarfs than B=0.05. It is the n=3 model (B=0.5, q_0 = 0.5; triangles) which provides the best fits to all the data. The percentage of galaxies predicted by the models to be located beyond the highest redshifts shown in the Figure are: $\sim$ 4% ($q_0 = 0.5$) and $\sim$ 1% ($q_0 = 0.05$) for B:21-22.5, $\sim$ 10% (q_0 = 0.5) and $\sim$ 2% (q_0 = 0.05) for I:17-22, $\sim$ 6% (q_0 = 0.5) and $\sim$ 0.4% (q_0 = 0.05) for K:18-19 and $\sim$ 17% ($q_0 = 0.5$) and $\sim$ 24% ($q_0 = 0.05$) for B:22.5-24. The three flat models on the one hand, and the two open models on the other, give very similar percentages for the predicted high redshift population.

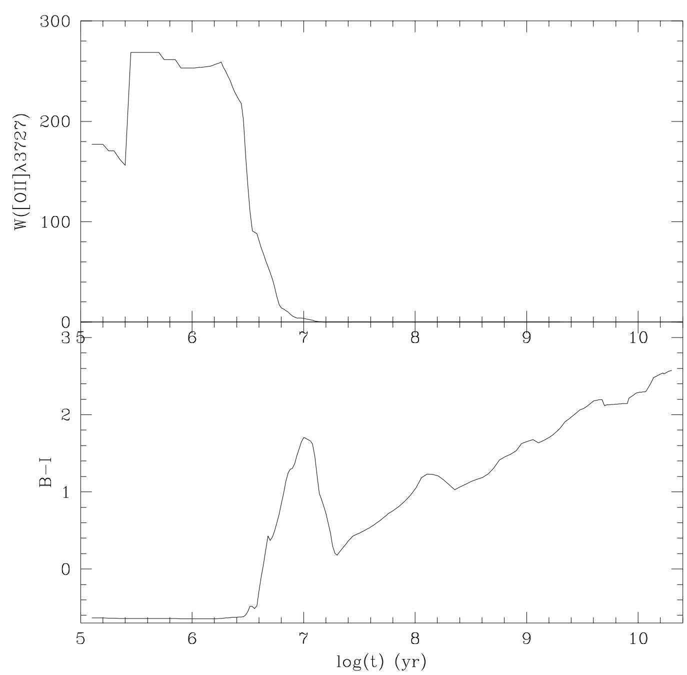

Fig. 8.— The evolution of the [OII]λ 3727 equivalent width and the B-I color with time after a single, instantaneous burst of star formation (the model has been kindly provided by G. Magris).

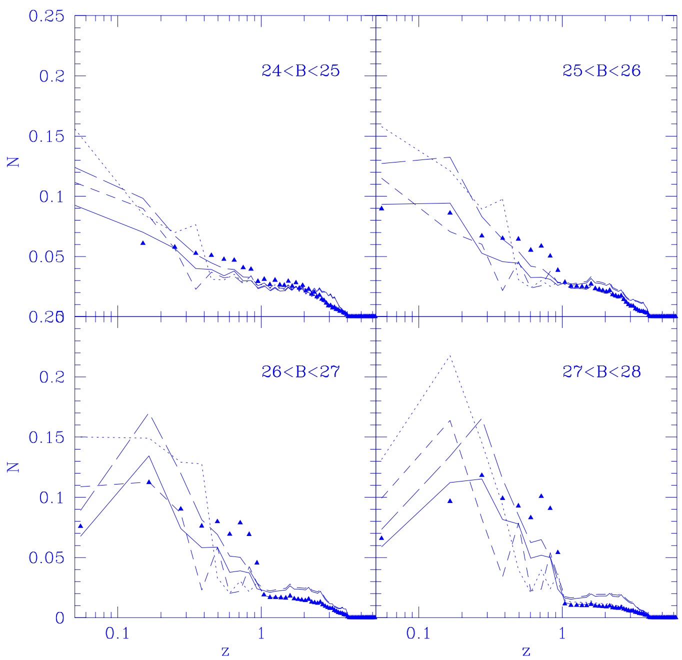

Fig. 9.— Model predictions for four (faint) magnitude bins. Lines and triangles are for different dwarf models as in Figure 7.

sured by Loveday et al. (1992) and Marzke et al. (1994) (arbitrarily normalized, because of the inconsistency between the two LFs). The LF0 shown here correspond to the B=0.5 model. It can be seen that the steep slope measured by Marzke et al. (1994) is, within the errors, consistent with the model. Notice that the slope of the LF for each generation of dwarfs is very steep, but the superposition of all dwarfs from the different generations plus giants at z=0 gives a much flatter slope, except at magnitudes fainter than ~ -15.

3.4. Angular size distribution

One of the most "puzzling" results that came out from the HDF concerns the sizes of the galaxies. The HDF is filled with apparently too many "little tiny" galaxies. Merging may help to solve the problem, by assuming that galaxies at high redshifts are splitted into the (smaller) fragments that will eventually merge to build up the present-day population (see Im et al. 1995, Roche et al. 1997). Another possible explanation is found in the dwarf-rich models, where a large contribution to the faint counts comes from intrinsically small (dwarf) galaxies. In order to check the viability of the models analised here next I show predictions for the angular size distribution of the galaxies in the HDF. (The isophotal angular sizes of the HDF galaxies shown in the Figures were measured by N. Metcalfe, who kindly provided me with the data previous to publication).

To compute the angular size distribution it is first neccesary to find relationships between physical size and absolute z=0 B-band luminosity of the galaxies. As in Im et al (1995), for ellipticals the scaling laws derived by Binggeli, Sandage & Tarenghi (1984) were used; $\log(r_{hl}/kpc) = -0.3(M_B + 18.75)$ if $M_B < -20$ and $\log(r_{hl}/kpc) = -0.1(M_B + 15.7)$ if $M_B > -20$, where r_{hl} is the model-independent half-light radius. The profiles are assumed to fit a de Vaucouleurs law, and the Kormendy's relationship is used to relate the effective radius with the effective surface brightness (μ_{eff}): $\mu_{eff} = -2.5\log(r_{eff}) + 20.2$ (the zero-point of the relation was taken from the work by Jørgensen, Franx & Kjærgaard 1995 for ellipticals in the Coma cluster). Notice that here I assume the half-light radius to be the same than the de Vaucouleurs effective radius, which will only be true as long as the de Vaucouleurs law is a good fit to the light profiles (see Binggeli, et al. 1985). The angular sizes of the HDF shown in the Figures are isopho-

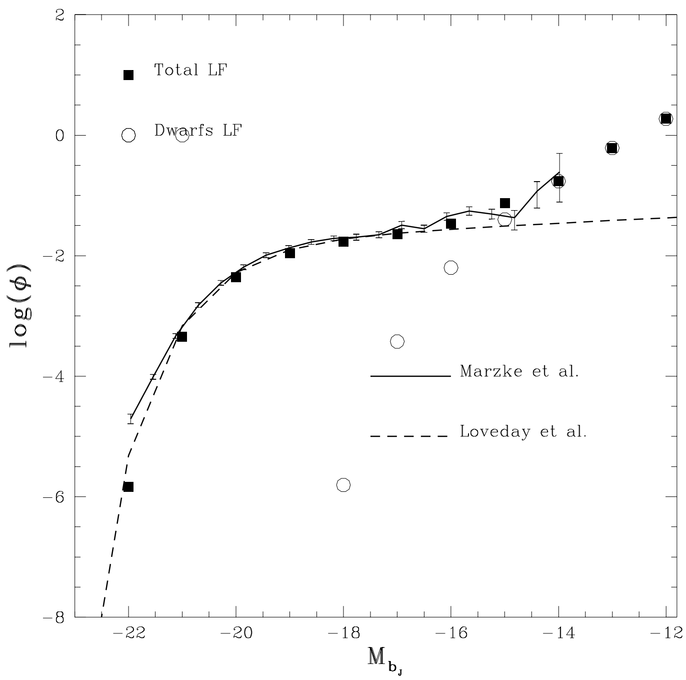

Fig. 10.— The z=0 LF from Loveday et al. (1992) and Marzke et al. (1992; the magnitudes has been shifted by 0.7 to fit Loveday's LF). Also shown is the LF0 in the B=0.5 n=0 model.

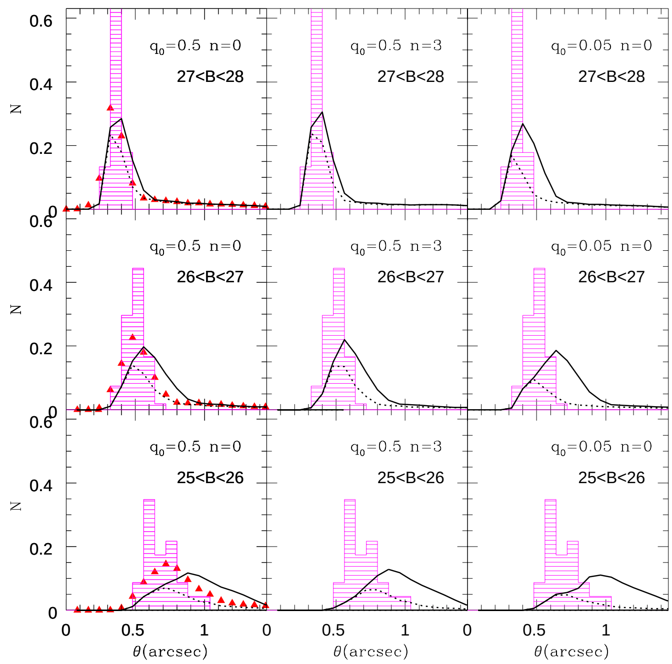

Fig. 11.— The isophotal angular size distribution of HDF galaxies (see text) and predictions from different B=0.5 models. Solid lines are for the total population of galaxies, whereas dotted lines are for the dwarf galaxies. Triangles are predictions from the model when spiral disk evolution is included.

tal sizes, defined by the isophote $\mu_B = 28.5$ mag per square arcsec. Assuming a de Vaucouleurs profile, the physical $r_{28.5}$ size corresponding to the $\mu_B = 28.5$ isophote is computed by taking into account the surface brightness dimming: $\mu^*_{28.5} = 28.5 - 10\log(1+z)$. $\mu^*_{28.5}$ is the surface brightness of the (z=0) isophote that, at a redshift z, would be observed as 28.5 mag per arcsec square (see e.g. Sandage 1961). Then, $r_{28.5} = r_{eff}[(\mu^*_{28.5} - \mu_{eff})/8.325 + 1]^4$. Notice that the evolution of the luminosity (and the K-correction) is included in the modeling, but no size evolution has been assumed (this means, a uniform fade of the luminosity is considered). Regarding the modeling of ellipticals, it should be quoted here the work by Im, Griffiths & Ratnatunga (1997) who tested luminosity evolution and merging models by means of the distribution of angular sizes and colors in the Hubble Space Telescope Medium Deep Survey. The modeling of the ellipticals follow the same approach as in Im et al. (1995), which, as quoted before, is also followed in the present work. Im et al. (1997) show that for $20 < I < 21$ and $21 < I < 22$ simple luminosity evolution models (taken $q_0 = 0.5$ and $H_0 = 50$ km s^{-1} Mpc^{-1}) nicely reproduced the half-light angular size distribution whereas merging models predict too many small galaxies compared to the data.

According to Freeman's law (Freeman 1970), the central surface brightness of the disk component in spiral galaxies is nearly constant ($\mu_0(B) \sim 21.3$). Even if not properly understood yet, results have accumulated indicating the validity of this empirical law (Boroson 1981; Kent 1985; Bosma & Freeman 1993). The fact that the central surface brightness is constant (though with a scatter of about 0.5-1 mag., see e.g. de Jong 1995, Marquez & Moles 1997) implies that the scale length and the luminosity of disk components are correlated: $\log(r_0/kpc) = -0.2M_B - 3.45$. As pointed out by Im et al. (1995), in modeling the spirals complications arise because the galaxies are not pure disks but also show a bulge component. To overcome this problem, Roche et al. (1997) model the half-light radii of spirals r_{hl} by considering that $r_{hl} = 1.4r_0$ for the early-types, instead of the "pure-disk" relationship $r_{hl} = 1.68r_0$ which is used for the late types. In the present work, because a single spiral type is considered, all spirals have been modeled as pure disks. Therefore we will have to keep in mind that the sizes will be slightly over-estimated. As for the ellipticals, the surface brightness dimming is taking into account in computing the isophotal angular sizes, and no size evolution is considered. I'll get back to this point at the end of the section.

The above empirical relationships allow, in a first simple approach, to compute predictions for the angular size distribution of "bright" galaxies. For dwarfs the situation is much more uncertain. As pointed out by Impey, Bothun & Malin (1988), studies about the structural parameters of dwarf galaxies are "obscured" by all kind of selection effects due to the intrinsic faintness of the objects. Nevertheless it is already well known that the light profiles of dwarf ellipticals (dEs) obeys a simple exponential law (Binggeli et al. 1984; Ichikawa, Wakamatsu & Okamura 1986; Caldwell & Bothun 1987; Impey et al. 1988). However for the dwarf irregulars (dIrrs) the situation is less clear as some of them show an excess of light over the exponential fit in the central parts (Bothun et al. 1986). With respect to the Blue Compact Dwarfs (BCDs), at least some of them seem to have surface brightness profiles that can be fitted by exponentials (Bothun et al. 1986; but see also Kunth et al. 1988). This situation has led to the suggestion that (some of) the BCDs might be the truly progenitors of the dEs, but it is less clear that dIrrs could evolve into dEs. On this respect Bothun et al. propose that there might be a continuous spectrum of dwarfs, and even if they all could eventually be stripped off the gas, the gas depletion process as well as the star formation efficiency might be quite complex, probably related to the gravitational potential well in which the gas in embedded.

Compared to the picture that emerges from the observations, the modeling of dwarfs in the present work is obviously quite simplistic. A single type of dwarf is considered, with a star formation process lasting 0.05 and 0.5 Gyr (depending upon the model considered). These numbers must be taken as a very first approximation to the star formation period of the "average" dwarf, as it seems clear that the star formation process and the gas depletion will not be the same for all dwarfs. Nevertheless it should be pointed out that, by allowing the star formation process to last over a relatively long period of time, the model is implicitly assuming that the gas depletion is more complex than in the simpler case in which the galaxies fade away after a single burst of star formation. A second problem to deal with is the evolution of the galaxy sizes as the luminosities fade. On this respect Binggeli (1985) has proposed two different scenarios: 1) uniform fade, i.e. the scale length will be preserved, and 2) faster fade

in the inside regions where the star formation could be more concentrated.

Continuing with the simple approach in the modeling of dwarfs, here I'll assume a single exponential fit for all dwarfs with constant central surface brightness *at the peak of the star formation process,* ($\mu_0(peak) \sim 21$), together with a uniform fade in luminosity. Like for the spirals, an exponential profile with a constant central surface brightness (that of course will fade at the same ratio than the luminosity) implies a correlation between total luminosity *at the peak of star formation* and scale length. For the B=0.5 model, where $M^*_{peak} = -18.5$ (see Table 2), a M^* dwarf would have a disk scale length of ~ 3.5 kpc, whereas for the smallest dwarfs ($M_{peak} = -13.5$) $r_0 \sim 0.4$ kpc. The existence of a correlation between luminosity and scale length for dwarf ellipticals has been shown by Binggeli et al. (1985) among others. For BCDs, Campos, Moles & Masegosa (1990) have shown the existence of a well-defined correlation between luminosity and isophotal radius of the form: $\log(L_{25}(B)) \propto 1.88 \log(R_{25})$. The slope of the correlation, very close to 2, implies a nearly constant surface brightness inside the 25 mag per square arsec isophote, as it is in fact observed ($\mu_{25} \sim 23.5$) though with a large (~ 1.5 mag) scatter. The scatter is interpreted in this paper as reflecting the fade in luminosity already at the BCD stage. Assuming an exponential surface brightness profile for dwarfs, and taking $\mu_{25} \sim 23.5$ for BCDs which could be considered as dwarfs observed $\sim$ very close to the *peak of the star formation process,* it is derived that $\mu_0(peak) \sim 21$.

In Figure 11 they are shown predictions for the B=0.5 model for 3 different cases: $q_0 = 0.5$ (with $n = 0$ and $n = 3$), and $q_0 = 0.05$ (with $n = 0$). Solid lines are predictions for the total angular size distribution, whereas dotted lines correspond to the dwarfs. The histograms are normalized to the total number of galaxies in each of the magnitude bins. As can be seen, for the faintest bin ($27 < B < 28$) the model(s), in spite of its simplicity, fits remarkably well the data (especially if $q_0 = 0.5$). For the brighter bins, in particular for the $25 < B < 26$ one, the models predict too large sizes compared to the data. It should be noticed that the contribution to the "un-observed large" galaxies comes from the "bright" population, as dwarf sizes fall well into the observed range.

In order to get some insight into the sources of discrepancy between data and models, (even if this goes beyond the goals of this paper which mainly addresses the role of dwarfs in the faint counts), let us go back to the modeling of the spirals. As said before, spirals are treated as single "pure" disks with no size evolution. Already the first assumption, i.e. neglecting the bulge, makes the sizes to be over-estimated. Also, it has been largely suggested in most models about the formation and evolution of disk components (see e.g. Lacey & Fall 1985; Wang & Silk 1994; Cayon, Silk & Charlot 1996), that disks are very likely formed from inside outwards as the gas is slowly falling from the halo to develop the disk . Just to check the effect of the "disk growth" in the predictions, let us model it in a very crude way as: $\log(r_0/kpc, z) = -0.2M_B + 3.45(1 + n \times z)$ with $n = 0.03$. (This means, for $z = 1$ and $z = 2$ galaxies the disk lengths will be a factor of ~ 1.2 and ~ 1.5 smaller than for $z = 0$ galaxies). Adding this (totally) "ad hoc" disk evolution, the predictions now (triangles in the Figure) fit the data also for the brighter bins and discrepancies smooth away.

4. Discussion

The phenomenological model for dwarfs shown here is somewhat *ad hoc*, due to the lack of knowledge about how dwarfs are formed are evolved. Nevertheless it is based on reasonable assumptions such as the formation at low-z when the UV-background ionization decreases (Babul & Rees 1992) or stars being formed during a "finite" period, the luminosity of the galaxy fading away afterwards (if stars where continuously formed, the metallicity would not keep at the low levels observed among dwarfs).

For how long does the star formation period take place? If counts and colors in the HDF are to be fitted by means of the dwarf population, the star formation period has to be quite long, at least few times 10^8 years. As it was shown in the last section, using shorter periods requires of larger numbers of dwarfs to fit the deep counts, which results in a large number of red, faint remnants not seen in the HDF. (It should be said here that, for the B=0.05 model, a time-consuming trial and error test - i.e. variations of α, n, $M_*(peak)$ - showed that there is no choice of a set of parameters able to provide good fits to the data).

In the "standard" model for dwarfs it is suggested that the star formation takes place in the form of single, very short bursts. As first shown by Dekel & Silk (1986), the shallow potential well of the galaxy is not

likely to be able to retain the gas after the explosions of few supernovae. This vision has been challenged by the analysis of the photometry of individual stars in nearby dwarfs. For example, in the Carina dwarf spheroidal galaxy by Smecker-Hane et al. (1996). In this very low mass galaxy the star formation history has been very complex: several bursts each one lasting $\sim$ 1 Gyr followed by quiescent periods. In order to explain this complex history together with the low metal content in the Carina galaxy, the authors suggest that the "gentle" star formation during the "active" phases generated winds which expelled the metal-enriched gas. But in order to keep the star formation without stripping the galaxy off, these winds cannot be strongly coupled with the general interstellar medium, and so denser gas clouds are not expelled from the galaxy. Therefore there must exist a sort of self-regulation mechanism able to keep a low-rate (gentle) star formation process for long periods without increasing the metal content. The gas might be eventually lost, but the gas depletion could be a very slow process, perhaps due to the presence of a massive dark halo.

A case of *anomalous* chemical enrichment in local dwarfs was found in GR8. This low metallicity galaxy ($Z \sim 1/18 Z_{\odot}$) shows a high helium content, a fact interpreted as the result of a selective metal lost during a *gentle* process of star formation (Moles, Aparicio & Masegosa 1990). In the same line, Masegosa, Moles & Campos (1994) analised a sample of 121 HII galaxies, finding no trend between the Helium abundance and the metallicity of the systems. Again, this result was interpret as reflecting the inability of the galaxy to retain the supernova ejecta, though the star formation phase in those systems is still an on-going process.

In the best model (B=0.5) for dwarfs used here each galaxy under-goes a single period of star formation lasting 0.5 Gyr, fading away afterwards. If the period of activity was longer and/or galaxies underwent multiple bursts, the number of dwarfs requires to fit the deep counts would be smaller, possibly in a better agreement with the observed n(z) distributions.

The B=0.5 model should be taken as a simple "statistical" approach to model dwarfs. This means that, on average, star formation in dwarfs may proceed in the form of intermittent periods of star-forming activity, each one lasting longer than a single *instantaneous* burst of star formation. The implication is that dwarfs should have a sort of self-regulation mechanism capable to inhibit an effective gas lost while keeping the low metal content. It is very plausible that this mechanism is related to the mass of the galaxy (or the dark halo) but also to the environment. An observational evidence of the latest is found in the dependence of the number of early dwarf-to-giant ratio with the richness of the environment (Ferguson & Sandage 1991). Our local group of galaxies is completely dwarf-dominated, with a LF extending over more than $\sim$ 13 magnitudes (van der Berg 1992). Some of the local dwarfs are red spheroidals depleted of gas, while some others (eg. Carina, GR8) show evidence that the star-forming activity has been proceeding over periods of several Gyrs. Therefore, a much more realistic model for dwarfs should account for the different evolutionary paths that dwarfs, depending on the dark halo mass, the environment, or both, have followed. Unfortunately little is known yet about the star formation history in these faint, small *(slippery)* systems.

In any case the purpose of the present work is to show that the inclusion of dwarfs is a "key" issue toward a proper interpretation of the deep counts of galaxies. The success of the very simple models in fitting both the counts in all different photometric bands and the colors of the faint galaxies in the HDF, while giving reasonable predictions for the redshift distributions supports this conclusion. Moreover, it seems clear that the very faint end of the counts is dominated by these intrinsically faint objects, i.e. reflects the faint end of the local LF. The inclusion of dwarfs also provides of a simple explanation to the large amount of "weirdos" objects observed in the deep HDF images. Nevertheless it is important to point out that some authors (eg. Ellis et al. 1996) have suggested that some of these peculiar systems may be sub-systems that will eventually merge to form ellipticals, although, as already mentioned, this merging process very likely occurred at high redshift ($z > 3$).

A further success of the models shown here comes from the fit to the angular size distribution of the galaxies in the HDF. Though the modeling of dwarfs is very simplistic, mainly due to the lack of enough observational grounds, still it was shown that the predicted angular sizes of the dwarf population fall well into the observed range. Discrepancies between data are models were found to be due to the "bright" galaxies, and in fact these are smoothed out when some disk size evolution is introduced.

The model of dwarfs proposed here to fit the counts, colors, redshifts and angular size distribution of faint galaxies relies into two parameters: the normalization (i.e. number density) of dwarfs and the star formation history. Whereas the first one is difficult to constrain due to the intrinsic faintness of these galaxies, the star formation history can be tested using local dwarfs, both following the approach by Smecker-Hane et al. of resolving individual stars but also by means of detailed studies of the chemical abundances.

The note of "pessimism" is given by the fact that adding "gentle" dwarfs to the models makes possible to fit counts, colors and redshifts both in the open and in the EdS case. Because the faint end of the counts are now dominated by low-z dwarfs, for which the normalization is, as remarked above, very uncertain (not to say totally un-known), q_0 won't be easily constrain by comparing the level of faint galaxies with the *availability* of large volumes at high-z. A way out is to measure the amount of high-z (eg. $z > 3$) galaxies at faint levels, following for example the U-drop procedure developed by Steidel et al. (1995). The ratio of low-z to high-z giants is more likely to provide a closer constrain on the value of q_0. For the I-band, where counts are comparatively deeper than in the other bands, the open models over-predict the counts at the faint levels while the EdS models provide a much better fit. However the uncertainties in the modeling of dwarfs do not allow to extract any strong conclusion from this.

Finally, it is worth noticing that testing the dwarf model, i.e. proving by means of redshifts that the bulk of faint galaxies in the deep counts is actually located at low-redshifts, has not only important implications for our understanding of the galaxy formation and evolution processes, but it provides of a further test to the standard cosmological framework. If bright counts were dominated by giants while the main contribution to the faint counts was given by dwarfs at lower-redshifts, this would imply that the counts of giants *flatten,* i.e. is leveling off as the volume elements at high-redshifts are increasing slower than in an Euclidean (d^3) geometry.

5. Summary and Conclusions

- The counts and colors of galaxies in the Hubble Deep Field can be easily fitted by simple luminosity evolution models which incorporate a numerous population of dwarf galaxies. Because of the present lack of knowledge on the space density of dwarfs, reasonable fits can equally be provided in both open and flat cosmologies. To constrain q_0 the high-z to low-z bright galaxies ratio is then needed, which requires of knowledge on the redshifts of the very faint population.

- The incorporation of dwarfs to the models provides of a simple explanation to the large number of *weirdos* galaxies seen in the deep Hubble images. While E and S counts can be fitted by means of simple pure luminosity evolution models, the high level of W counts requires of an extra-population of dwarfs. Previous claims that the results from the counts as a function of morphology either challenge the morphological classification system and/or support that strong merging is present at low-to-moderate redshifts are no longer sustained.

- In order to fit the counts to the very faint levels by means of dwarfs it is neccesary to invoke that the star formation history in dwarfs is more complex than previously thought. Models in which the star formation takes place in single, very short episodes predict large amounts of red remnants not seen in the HDF deep counts. By allowing the star formation to take place over longer periods the number of remnants is severely reduced, and the color distribution of very faint galaxies in the HDF can be nicely fitted. Then, a kind of self-regulation mechanism capable to keep the low metal content in dwarfs while the star formation is lasting for longer period has to be invoked. Observational evidence for the complexity of the evolutionary path followed by dwarfs has been found (eg. Smecker-Hane et al. 1996) in local dwarfs.

- As a further test to the simple dwarf-rich models shown here the isophotal size distribution of the HDF galaxies was compared with predictions from the models. It was found that model-dwarf sizes are comparable to the observed sizes of the HDF galaxies, though to fit the distribution of the whole population it was neccesary to include some disk size evolution for the spirals.

I wish to acknowledge helpful discussions with Tom

Shanks, Nigel Metcalfe, Dick Fong, and Jon Gardner. I also thank Mariano Moles for his careful reading of this manuscript, Nigel Metcalfe for the help with the HDF data, and the referee, Henry Ferguson, whose comments helped to largely improved the paper. This work was supported by an EU fellowship, and a Spanish CSIC grant.

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Table 1: Model Parameters for Bright Galaxies

Table 1: Column 1: Type of galaxy; Columns 2-4: LF0 parameters ($H_0 = 50$ km s^{-1} Mpc^{-1}); Columns 5-7: IMF, SFR e-folding time and redshift of formation

Type	Φ^* (Mpc^{-3})	M_B^*	α	IMF	τ_e (Gyr)	z_{for}
E	9.5×10^{-4}	-20.9	-0.48	Scalo	1 ($q_0 = 0.05$) / 0.7 ($q_0 = 0.5$)	4 ($q_0 = 0.05$) / 7 ($q_0 = 0.5$)
S	1.15×10^{-3}	-21.1	-1.24	Scalo	10 ($q_0 = 0.05$) / 7 ($q_0 = 0.5$)	4 ($q_0 = 0.05$) / 7 ($q_0 = 0.5$)
Irr	5.4×10^{-4}	-21.1	-1.24	Salp	constant	4 ($q_0 = 0.05$) / 7 ($q_0 = 0.5$)

Table 2: Model Parameters for Dwarf Galaxies

Table 2: Column 1: Model; Column 2: Duration of the period of star formation; Column 3: q_0; Column 4: rate of dwarf formation (see text); Column 5: Φ^* for the generation of dwarfs forming at z=0; Column 6: M^* (in the peak of star formation); Column 7: α

Model	B	q_0	n	$\Phi_0^*(g(z=0))$ (Mpc^{-3})	M_B^*	α
1	0.05	0.05	0	5×10^{-3}	-20	-2
2	0.05	0.5	0	5×10^{-3}	-20	-2
3	0.5	0.05	0	3×10^{-3}	-18.5	-2
4	0.5	0.5	0	3×10^{-3}	-18.5	-2
5	0.5	0.5	3	1×10^{-3}	-18.5	-2